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Paleoenvironmental Reconstruction of the Late Cretaceous Eastern Gulf Coastal Plain in Georgia and Alabama

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PALEOENVIRONMENTAL RECONSTRUCTION OF THE LATE CRETACEOUS EASTERN GULF COASTAL PLAIN IN GEORGIA AND ALABAMA

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ABSTRACT

The present study reconstructs the regional paleoenvironment (particularly paleoclimate) of the Late Cretaceous Eastern Gulf Coastal Plain of Georgia and Alabama using paleobotanical, paleoecological and geochemical methods in order to evaluate the Late Cretaceous climate of the Southeastern United States, and to add to the body of paleoclimate data for that time. Paleobotanical analysis indicates a terrestrial mean annual temperature (MAT) of about 27°C during the Late Cretaceous, which is considerably warmer than modern terrestrial MAT. Stable oxygen isotope data from molluscan carbonate indicate mean sea surface temperature (SST) of 26.8 °C for the Santonian, 23.5°C for the early Campanian, and 28.8°C for the late Campanian. These paleotemperature compare with the modern Gulf Coast mean SST of about 21.8°C. Results of carbon stable isotope analysis for determination of paleosalinity show the method to be useful, but best used in conjunction with other methods, including paleoecological analysis. The study also explored the use of strontium isotopes for the determination of paleosalinity, as well as for geological age determination. Results suggest that further examination of strontium isotope analysis would be valuable.

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DEDICATION

This work is dedicated to the memory of my father, the late Albert R. Hall who encouraged my interest in science, inspired me to learn, and always believed I could accomplish anything I tried.

INTRODUCTION

"The farther backward you can look, the farther forward you are likely to see." – Winston Churchill

Despite continuing controversy and debate, a growing body of research provides a collective view of a warming world, along with other changes in the climate system. Global average surface temperatures have increased over the past century by about 0.5°C. The average increase in temperature over the twentieth century in the Northern Hemisphere is the largest of the past 1000 years (the 1990s were apparently the warmest decade), based on data from historical records as well as from multiple climate proxies. These proxies include pollen, tree rings, ice cores, and corals. There has been widespread retreat of mountain glaciers as well as secular decrease in snow cover, sea ice thickness, and duration of ice on lakes and rivers (Gutzler, 2000). Since the 1940s, ocean temperature has undergone a significant increase and global average sea level has risen between 10 and 20 cm. The projected increase in global average sea level at the end of this century ranges from 20 to 70 cm. (IPCC, 2001).

In light of these phenomena, much concern, debate, and controversy has ensued concerning the "greenhouse" effect on global climate and other aspects of climate change. Currently there is considerable uncertainty in our understanding of natural climate variability and of its impact on natural systems. This uncertainty emphasizes the importance of investigations of climate systems and climate variability, not only of historical records, but of prehistoric data as well. Reconstructions of pre-modern climate

periods enhance our understanding of modern Earth's climate systems and natural variability. Reconstructions of the Late Cretaceous period in particular, one of the warmest "greenhouse" episodes in Earth's history, address questions about the environmental characteristics of a greenhouse world.

Most climate prediction is accomplished using sophisticated computer models, which are actually simplifications of the climate system. Computer models provide insight into how the climate system responds to change, and tests hypotheses about causes of past environmental changes. Considerable research is focused on ensuring that these models can accurately simulate most aspects of modern climate dynamics, including climate change (Bradley, 1999; Cronin, 1999). Model simulations of past climate change and observations from the paleoclimate records must be used interactively, not only to assess the validity of climate model output, but to generate hypotheses about the nature and causes of environmental change as well.

Paleogeographic and Geologic Setting

During much of the later Mesozoic Era, the Western Interior Seaway (WIS) bisected the North American continent (Figure 1), connecting oceanic areas of different climatic regimes: waters from both the northern boreal and subtropical (Gulfian) oceans flowed into the WIS and left distinctive floral and faunal assemblages (Hay et al. 1993). During the Late Cretaceous Epoch, North America was oriented clockwise relative to its present position, and the Eastern Gulf Coastal Plain lay in a nearly east-west configuration (Scotese et al. 1988). The paleolatitude of the Chattahoochee River Valley region at that

time was approximately the same as present day; however, the Eastern Coastal Plain from Tennessee to New Jersey had a decreased latitudinal gradient than at present, and the Gulf Coast shoreline adjoining the WIS had a slightly increased latitudinal gradient (Schwimmer 2002). No modern analog for these conditions exists.

The Southeast is particularly significant to studies of ancient paleoenvironments because the preservation of nearshore marine deposits is exceptional in this part of the Gulf Coastal Plain, and represents one of the most complete Upper Cretaceous sedimentary sections in North America (Reinhardt and Gibson, 1981; Reinhardt and Donovan, 1986). Nonetheless, there is great disparity in the volume of scientific work addressing the eastern and western margins of the Seaway.

All Late Cretaceous deposits in the Chattahoochee River Valley younger than Cenomanian Age (~90.5 Ma.) are marine or marginal-marine in nature, preserving records of four marine transgressive-regressive cycles (Reinhardt and Donovan 1986). These Upper Cretaceous marine deposits are the Eutaw, Blufftown, Cusseta, Ripley, and Providence Sand Formations, successively (however, the Ripley and Providence Sand Formations will not be included in this study). A map of the general area under study is shown in Figure 2.

The Eutaw Formation is the oldest formation of Cretaceous age definitely of marine origin (Eargle 1955). An initial marine transgression marks the base of the Eutaw, followed by a regressive phase that lasted, with minor fluctuations, for the remainder of the Santonian (Reinhardt and Donovan 1986). Frazier (1982; 1987) interpreted the Eutaw

Formation in western Georgia to be the result of deposition along a barrier-barred coast, composed of a variety of specific environments including barrier, littoral, and paludal.

Overlying the Eutaw Formation, the Blufftown Formation has been informally divided by Reinhardt (1986) into a lower and an upper part based on an interpretation of two depositional cycles resulting from two separate transgressive events. According to Schwimmer (1986), the local stratigraphy at Hannahatchee Creek suggests considerable fluctuations in sea level, as well as sequences of probable storm deposits. The paleoenvironment of the Blufftown Formation represents marine, non-marine, and paralic habitats. The Hannahatchee Creek locality is assumed to represent an ancient estuary because of sedimentary structure and texture, presence of non-marine vertebrate fauna, fossil wood, and combined marine and brackish-water fauna (Schwimmer 1997, 2002). However, Schwimmer (2002) points out that estuarine deposits are not easily identifiable because such sediments are nearly identical to those formed in other nearshore environments, especially back-barrier lagoons, and are best determined by using fossil assemblages. (This approach, however, can be problematic since it can be difficult to determine if a specific coastal fossil assemblage formed in place.)

The suprajacent Cusseta Formation represents deposition during an interval of relatively stable shoreline configuration, following establishment of the coastal barrier complex in the updip beds. The thin carbonaceous clay and sand interval just below the Cusseta-Ripley boundary is interpreted as the result of deposition in a restricted back barrier environment, indicating a terminal regressive phase (Reinhardt et al. 1994).

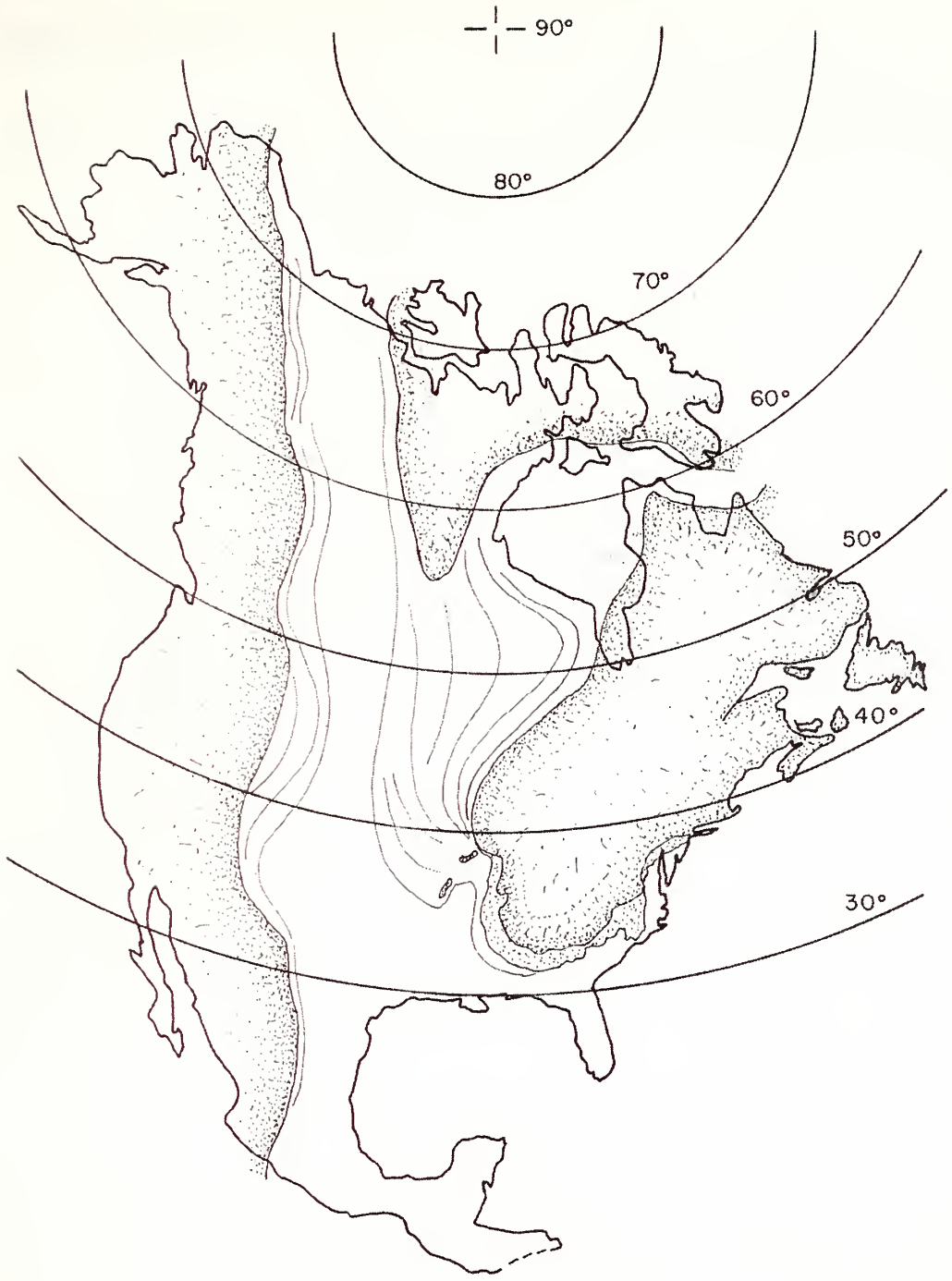
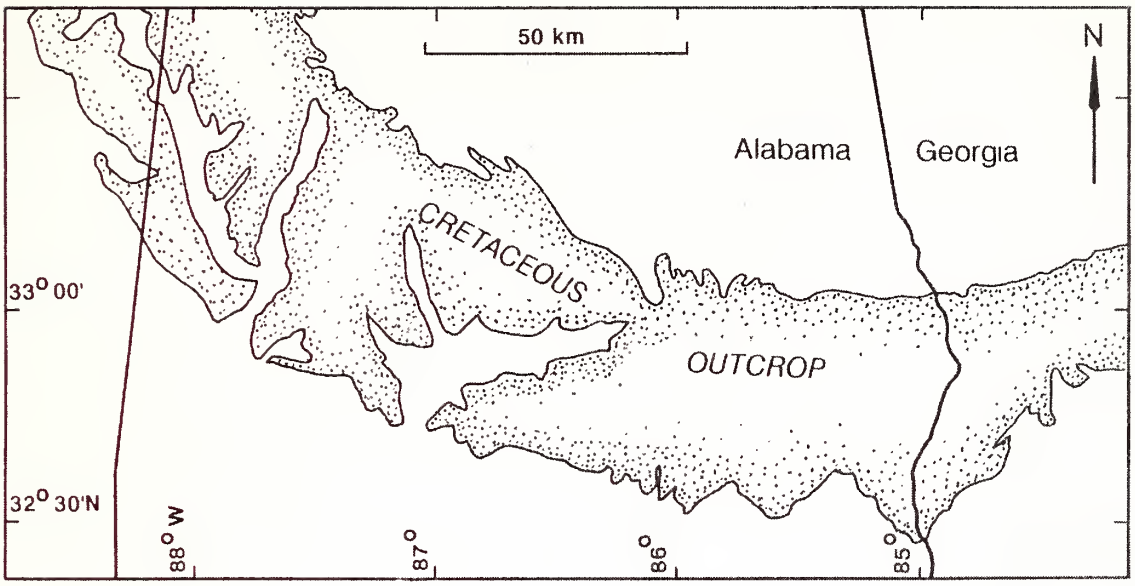


Figure 1: North America during the Late Cretaceous

Figure 2: Study area



THEORY AND METHODS

The present study reconstructs the regional paleoenvironment (particularly paleoclimate) using paleobotanical, paleoecological, and geochemical isotope methods. By this practice, the limitations of any one method can be at least partially overcome by integrating information gained from several different methods and taxa. An integrated approach to paleoenvironmental reconstruction will also lead to a more thorough analysis of the paleoenvironmental controls influencing the distribution of organisms in a given habitat.

Paleobotanical Analysis

Theory

It has long been observed that much of a plant's response to its environment is expressed in its leaf morphology. Certain characteristics of angiosperm leaves in particular have been used for paleoclimate study, including the presence of drip tips, leaf size, and margin type, among others. Bailey and Sinnot (1915, 1916) were the first to observe a positive relationship between mean annual temperature (MAT) and the proportion of entire-margined leaves in modern floras by demonstrating that most species in tropical climates had entire margins, and that non-entire margins dominated in temperate regions. This relationship is particularly significant to paleoclimate studies using fossil leaves because it is independent of taxonomy. Between the time of these initial studies and the 1970s, leaf physiognomy as a paleoclimatic tool was applied only

in a general manner, without numerical parameters. Wolfe (1979) used an extensive dataset (50 species or more in most samples) from eastern Asian forests to quantify this relationship using linear regression. His data indicated that in broad-leaved humid to mesic forests, percentages of entire-margined species increased at a linear rate of about 3% per degree Celsius. Application of this method to fossil floras is known as Leaf Margin Analysis (LMA). Wolfe (1993) attempted to improve the precision of paleotemperature estimates with the Climate-Leaf Analysis Multivariate Program (CLAMP) using a multivariate dataset of 29 leaf characteristics per sampling site, derived primarily from North American forests. This approach was also intended to provide a method to infer other climatic variables, such as seasonality of temperature, and amount and seasonality of precipitation. However, Wilf (1997) argued that the significance of the majority of the CLAMP characters for estimating climatic variables besides MAT is poorly substantiated, and that the use of additional characters from CLAMP contributes little information about temperature. He demonstrated that LMA, rather than multivariate techniques based on CLAMP, remains the most parsimonious, effective, and unambiguous method for estimating terrestrial paleotemperatures. Further, estimates from LMA have shown general agreement with other geologic paleotemperature proxies (Parrish and Spicer, 1988; Wilf, 1997). In regard to studies of fossil floras, leaf margin type offers important advantages over other morphological characters, such as leaf size, in that leaf margin type is easily and unambiguously scored, and taphonomic bias has little influence (Wilf 1997). For these reasons LMA, rather than CLAMP, is the method

used in the study at hand. Accuracy of mean annual temperature estimates from leaf margin analysis is dependent on sample size. Wolfe (1993) determined that samples containing 20 or more species provide the most accurate results, with standard errors ranging from 0.7°C to 1.0°C.

Methods

Edward Berry (1914, 1919) published descriptions of fossil plants collected from several Upper Cretaceous localities in the Eastern Gulf Region, along a belt extending from west-central Tennessee to west-central Georgia. Most of the fossil plants he described came from the Cenomanian-age Tuscaloosa Formation; however, there was enough material from the overlying Eutaw Formation to be used for LMA to provide paleotemperatures for the Santonian Age. Unfortunately, the suprajacent (Campanian Age) Blufftown Formation contains a flora too meager to be useful for LMA.

The Eutaw flora described by Berry (1914, 1919) is dominated by dicotyledonous angiosperms (Table 1). The flora also includes one fern, two monocotyledons, and nine gymnosperms (*Araucaria bladenensis* and *Sequoia reichenbachi* being the most abundant of these). Fossil plant remains have been recovered from Upper Cretaceous deposits by other workers; however, Berry's is apparently the only well-described, large-scale survey of the paleoflora of the region. Although he described 31 angiosperm species present in the Eutaw Formation, five of the species were found only at a locality in Tennessee, which were excluded from the present analysis because the Tennessee locality is outside the geographical range of this study.

For the present analysis, the sample consists exclusively of the 26 species present in the Eutaw Formation of Georgia and Alabama and described by Berry in his 1919 survey. The proportion of entire vs. non-entire (toothed) margins was calculated based primarily on Berry's detailed morphological descriptions and/or figures. Where his descriptions were lacking, margin type was determined using other sources (Berry 1904, 1906, 1914; Lesquereux 1892; Newberry 1895). Following Wilf (1997), unvascularized crenulations or irregular edges, and lobed leaves without teeth on the lobes, were scored as entire. Only one species (*Salix eutawensis*) having toothed margins was present in the Eutaw sample, so that the percentage of entire-margined species in the sample is 96.2 (Table 2).

Table 1: Santonian Age flora of the Coastal Plain (from Berry, 1914)

Plant name	Class	Order	Family
Andromeda cretacea	Angiospermae (dicot)	Ericales?	Ericaceae
Andromeda novaecaesareae	Angiospermae (dicot)	Ericales?	Ericaceae
Andromeda parlatorii	Angiospermae (dicot)	Ericales?	Ericaceae
Andromeda wardiana	Angiospermae (dicot)	Ericales?	Ericaceae
Androvettia elegans	Gymnospermae	Coniferales	
Aralia eutawensis	Angiospermae (dicot)	Apiales	Araliaceae
Araucaria bladenensis	Gymnospermae	Coniferales	
Araucaria jeffreyi	Gymnospermae	Coniferales	
Bauhinia alabamensis	Angiospermae (dicot)	Fabales	Fabaceae
Bauhinia cretacea	Angiospermae (dicot)	Fabales	Fabaceae
Brachyphyllum macrocarpum formosum	Gymnospermae	Coniferales	
Cephalotaxospermum carolinianum	Gymnospermae	Coniferales	
Cinnamomum heeri	Angiospermae (dicot)	Laurales	Lauraceae
Cinnamomum newberryi	Angiospermae (dicot)	Laurales	Lauraceae
Cupressinoxylon sp.	Gymnospermae	Coniferales	
Dewalquea smithi	Angiospermae (dicot)	Ranunculales?	Ranunculaceae
Diospyros primaeva	Angiospermae (dicot)	Ebenales	Ebenaceae
Doryanthites cretacea	Angiospermae (monocot)	Liliales	
Eucalyptus angusta	Angiospermae (dicot)	Myrtales	Myrtaceae
Ficus crassipes	Angiospermae (dicot)	Urticales	Moraceae
Ficus krausiana	Angiospermae (dicot)	Urticales	Moraceae
Ficus ovatifolia	Angiospermae (dicot)	Urticales	Moraceae
Juglans arctica	Angiospermae (dicot)	Juglandales	Juglandaceae
Laurophyllum elegans	Angiospermae (dicot)	Laurales	Lauraceae
Laurus plutonia	Angiospermae (dicot)	Laurales	Lauraceae
Magnolia boulayana	Angiospermae (dicot)	Magnoliales	Magnoliaceae
Magnolia capellinii	Angiospermae (dicot)	Magnoliales	Magnoliaceae
Malapoenna horrellensis	Angiospermae (dicot)	Laurales	Lauraceae
Manihotites georgiana	Angiospermae (dicot)	Euphorbiales	Euphorbiaceae
Menispermites variabilis	Angiospermae (dicot)	Ranunculales	Magnoliaceae
Myrcia havanensis	Angiospermae (dicot)	Myrtales	Myrtaceae
Paliurus upatoiensis	Angiospermae (dicot)	Rhamnales	Rhamnaceae
Phragmites pratti	Angiospermae (monocot)	Graminales	
Phyllites asplenioides	Uncertain	Uncertain	
Pterospermites carolinensis	Angiospermae (dicot)	Malvales?	
Salix eutawensis	Angiospermae (dicot)	Salicales	Salicaceae
Salix flexuosa	Angiospermae (dicot)	Salicales	Salicaceae
Salix lesquereuxii	Angiospermae (dicot)	Salicales	Salicaceae
Sequoia ambigua	Gymnospermae	Coniferales	
Sequoia reichenbachi	Gymnospermae	Coniferales	
Tumion carolinianum	Gymnospermae	Coniferales	
Zizyphus laurifolius	Angiospermae (dicot)	Rhamnales	Rhamnaceae

Table 2: Dicotyledonous angiosperms of the Eutaw Formation (from Berry, 1914)

Plant name	Margin
Andromeda cretacea (bog rosemary; Heath family)	entire
Andromeda parlatorii (bog rosemary; Heath family)	entire
Andromeda wardiana (bog rosemary; Heath family)	entire
Aralia eutawensis (spikenard; Ginseng family)	entire
Bauhinia alabamensis (bauhinia; Pea family)	entire
Bauhinia cretacea (bauhinia; Pea family)	entire
Cinnamomum heerii (cinnamon; Laurel family)	entire
Cinnamomum newberryi (cinnamon; Laurel family)	entire
Diospyros primaeva (persimmon; Ebony family)	entire
Eucalyptus? angustus (gum; Myrtle family)	entire
Ficus crassipes (fig; Mulberry family)	entire
Ficus krausiana (fig; Mulberry family)	entire
Ficus ovatifolia (fig; Mulberry family)	entire
Juglans arctica (walnut; Walnut family)	entire
Laurus plutonia (Laurel family)	entire
Magnolia boulayana (magnolia; Magnolia family)	entire
Magnolia capellinii (magnolia; Magnolia family)	entire
Malapoenna horrellensis (Laurel family)	entire
Manihotites georgiana (Spurge family)	entire
Menispermites variabilis (Moonseed family)	entire
Myrcia havanensis (rodwood; Myrtle family)	entire
Paliurus upatoiensis (Jerusalem thorn;Buckthorn family)	entire
Salix eutawensis (willow; Willow family)	toothed
Salix flexuosa (willow; Willow family)	entire
Salix lesquereuxii (willow; Willow family)	entire
Zizyphus laurifolius (jujuba; Buckthorn family)	entire

Geochemical Analyses

Theory

INTRODUCTORY STATEMENT

Isotopic ratios of oxygen ($^{18}O/^{16}O$), carbon ($^{13}C/^{12}C$), and strontium ($^{87}Sr/^{86}Sr$) were analyzed to obtain information about Late Cretaceous ocean water conditions. Stable isotopes of oxygen and carbon provide quantitative information about paleotemperatures and paleosalinity regimes; strontium isotopes can provide useful information about geologic age as well as paleosalinity.

OXYGEN ISOTOPE ANALYSIS

Oxygen isotopes obtained from marine calcareous fossils have been used extensively in paleotemperature determination. When a mollusc deposits shell carbonate in equilibrium with the ambient seawater, the oxygen isotopic composition of the shell reflects the temperature and $\delta^{18}O$ composition of the water. Oxygen (and carbon) isotopes are reported as ratios of heavy to light isotopes, and are expressed in delta (δ) notation; changes in ratio result from fractionation of the isotopes during biologic and physical processes. Because of the differences in the energy levels of isotopes, oxygen isotope fractionation is, in part, a function of temperature, so that as temperature increases, the proportion of ^{16}O goes up relative to ^{18}O. For example, if carbonate is formed at 20°C, it will contain a higher proportion of ^{16}O than if it formed at 10°C (Parrish, 1998). Light isotopes also preferentially evaporate due to their higher vapor pressures. Evaporation from oceans results in water vapor that is depleted in ^{18}O. Poleward movement of the

^{18}O-depleted vapor and subsequent precipitation onto ice caps gives rise to ice caps that are isotopically lighter than the oceans.

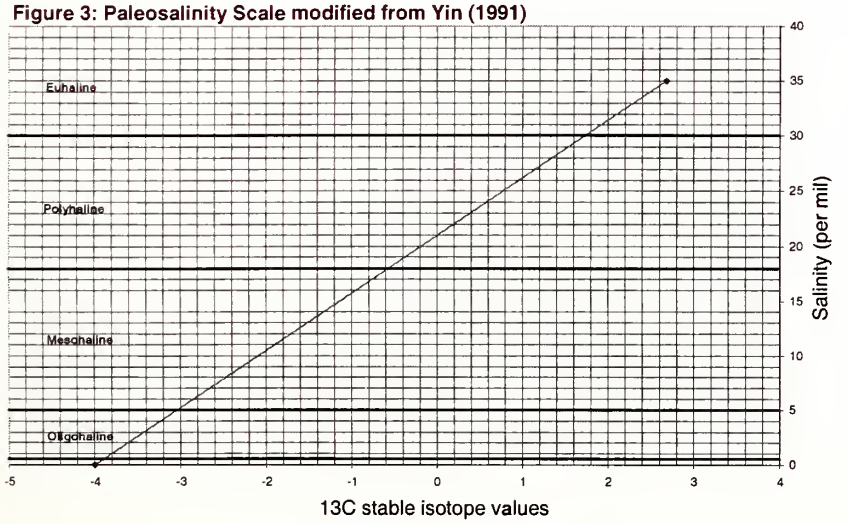
Isotopic composition of a rock or fossil is also controlled in part by the isotopic composition of the fluid in which it formed, and by the mineral phase (Faure, 1986). In some organisms however, there may be a characteristic departure of the isotopic composition of a shell from inorganic carbonate formed under the same environmental conditions, due to physiologic factors (so-called "vital effects"), thereby causing nonequilibrium precipitation of carbonate in some organisms. Taxa that show large vital effects include coral and echinoderms, whereas molluscs, foraminifera, and brachiopods generally show negligible vital effects (Dodd and Stanton, 1991). Skeletal carbonates also commonly undergo diagenesis, which can alter the isotopic composition of the shells. Low-magnesium calcite is more stable than high-magnesium calcite and aragonite, and is generally regarded as having low diagenetic potential (Schönfeld et al., 1991; Parrish, 1998). Therefore, molluscs, which as a group deposit their shells in isotopic equilibrium with ambient seawater, and especially those whose shells are composed of primary low-magnesium calcite, such as oysters, belemnites, and rudistids, are ideal sources for oxygen isotope data.

CARBON ISOTOPE ANALYSIS

Carbon isotope content of shell carbonate has been used to reconstruct ancient salinity regimes (Mook, 1971; Yin, 1991; Yin et al., 1995). Based on the assumption that organisms secrete carbonate in isotopic equilibrium with seawater, and that the isotopic

composition of Cretaceous seawater was the same as that of present-day seawater, the carbon isotope values obtained from epifaunal organisms will reflect the isotopic composition of the seawater. Infaunal organisms are considered less reliable salinity indicators because they were more strongly influenced by geochemical processes acting on pore waters just below the depositional surface. Oxygen isotopes are influenced by salinity as well, but are much more affected by temperature and by diagenesis than are carbon isotopes. Yin (1991) demonstrated that marine, brackish, and freshwater bivalve shells can be distinguished based on their ^{13}C values and devised a salinity scale (Figure 3) to reflect this. The endpoints of the scale are based on ^{13}C values obtained from taxa known to have inhabited freshwater (0‰) and fully marine (35‰) environments. Quantitative salinity values can then be obtained by interpolation with the freshwater and the fully marine endpoints. In studies of Jurassic bivalves (Yin, 1991; Yin et al., 1995), paleosalinity reconstructions based on carbon isotope data has been shown to agree well with independent evidence from paleoecological analyses.

Figure 3: Paleosalinity Scale modified from Yin (1991)



STRONTIUM ISOTOPE ANALYSIS

Isotopes of strontium do not fractionate in the manner of oxygen and carbon; rather, strontium ratios represent changes in the isotopic composition of strontium contributed to ocean water from various distinct sources. Generally, old granitic basement rocks of the continents have high $^{87}Sr/^{86}Sr$ ratios, young volcanic rocks have low ratios, and marine carbonate rocks have intermediate values. Further, there is very limited production of radioactive ^{87}Sr by decay of ^{87}Rb in carbonate rocks because calcium carbonate permits Sr^{2+} to replace Ca^{2+} but does not permit the replacement of Ca^{2+} by Rb^{+}. For these reasons, carbonate rocks record the isotope composition of strontium in the fluid phase at the time of deposition. The strontium isotope composition is constant throughout modern oceans (Faure, 1991), and several isotope analyses of strontium ratios in Precambrian and Phanerozoic marine carbonates collected from different parts of the world (Veizer and Compston, 1974; Burke et al., 1982; Faure, 1986; Schmitz et al., 1991; Veizer et al., 1999; Cochran et al., 2002) have shown that $^{87}Sr/^{86}Sr$ has varied systematically with time, making strontium isotope ratios a useful tool for geologic age determination.

The use of strontium isotopes in determining paleosalinity has also recently begun to be explored, and several studies have been promising (Schmitz et al., 1991; Holmden et al., 1997; Reinhardt et al., 1998; Cochran et al., 2002). Determining paleosalinity from strontium isotope ratios relies on the fact that, at a given time, most freshwater environments have a strontium isotopic composition different from that of seawater. The

technique has been used with both carbonate shell material and biogenic apatite (Schmitz et al., 1991; Holmden and Hudson, 2000; Cochran et al., 2002). Because strontium isotopes do not fractionate, values are usually reported directly as a measured ratio rather than in delta notation. The global average ratio for present day river runoff is about 0.710-0.712. Present day seawater, on the other hand, is uniform with respect to $^{87}Sr/^{86}Sr$ and has a ratio of 0.7092 (Schmitz et al., 1991). Schmitz et al. (1991) concluded that fossil marine fish apatite, as much as 400 m.y. old, generally has the same Sr-isotopic composition as contemporaneous seawater, whereas fossil freshwater apatite generally gives isotopic ratios that are substantially higher than those for seawater of the same age. In a study completed by Cochran et al. (2002), fossil samples from four biofacies (offshore, nearshore, brackish, and freshwater) within the Cretaceous Western Interior Seaway, plus one locality representative of the open ocean, were analyzed for Sr isotopes in order to determine paleosalinities. The $^{87}Sr/^{86}Sr$ ratios showed significant and systematic decreases from marine to brackish facies. Although values within adjacent groups overlapped within the error, the overall trend was toward progressively lower values such that the brackish samples were significantly different from the open ocean samples.

Methods

Carbonate samples taken from oyster shells, plus one chalk sample, were analyzed for the stable isotopes of oxygen, carbon, and strontium. Twelve of the carbonate samples were analyzed by Geochron Laboratories for the stable isotopes of oxygen and carbon.

Two *Exogyra upatoiensis* specimens and two *Ostrea cretacea* specimens representing the Santonian-age Eutaw Formation were obtained from the Columbus State University paleontology collections. The *E. upatoiensis* specimens (KE03 and KE04) were originally collected from the Broken Arrow Bend locality along the Chattahoochee River, which was approximately 16 km. downriver from Columbus, in Chattahoochee County, but is no longer accessible as a result of the construction of the dam at Ft. Gaines, Georgia. The dam created Lake Eufaula, but also inundated Broken Arrow Bend and many other Late Cretaceous outcrops along the Chattahoochee River. Stephenson (1956) described the basal 0.5 to 2.5 meters of the Eutaw Formation at this site as medium to coarse, crossbedded sand and interbedded clay that contained lignified and petrified wood and fossil leaves. The overlying beds from which the oyster fossils (and other marine fossils) were collected were about 4.5 meters thick, and described as slightly laminated gray, micaceous sand and clay, with interbedded layers of calcareous concretionary nodules.

The *O. cretacea* specimens (KE01 and KE02) were originally collected from an outcrop along Upatoi Creek near Old Cusseta Road, in Chattahoochee County, now overgrown with vegetation and partially destroyed by human activity. Stephenson's (1956) description of the site is that of fossiliferous clay with irregular dark gray foliations and lignite fragments, containing discontinuous layers of nodular limestone and irregularly distributed calcareous concretions.

Three *Exogyra ponderosa* specimens (KB01, KB02, and KB04), representing the early Campanian-age Blufftown Formation, were collected from a shell bed along

Hitchitee Creek, in northwest Stewart County, about 7 km upstream from the Walter George Reservoir. The Blufftown Formation in this area of the Chattahoochee River Valley is described by Frazier (1977) as fossiliferous, dark gray, silty, micaceous, carbonaceous clay. Also representing the early Campanian, a chalk sample (CSU-K-96-6-1) from the Mooreville Formation of central Alabama was obtained from the CSU paleontology collections. The Mooreville Formation intertongues with the Blufftown Formation in eastern Alabama. The sample was an infilling of a crocodylian tooth alveolus collected from the Jones Bluff Lock and Dam site, on the Alabama River near the Lowndes-Dallas county line.

Two *Crassostrea cusseta* specimens (KC02 and KC03) collected from Hannahatchee Creek in Stewart County, were obtained from the CSU collections. These specimens represent the late Campanian-age Cusseta Formation. The bed from which these fossils were collected were described by Schwimmer (1986) as a lignitic and fossiliferous clayey fine sand and silty clay; this unit was originally described as the upper Blufftown Formation, but has since been reinterpreted as belonging to the basal Cusseta Formation (Schwimmer, pers. comm., 2005).

A separate set of carbon and oxygen isotope analyses were run by K. C. Lohmann at the University of Michigan on samples from some of the same specimens sent to Geochron Labs. Three separate samples were taken from specimen Kc03, three samples from specimen Kc05, and two samples from Kb04. Additional samples were taken from specimens that were not also sent to Geochron Laboratories, including two separate

samples from one *E. ponderosa* specimen, two samples from one *O. cretacea* specimen, and one sample from another *O. cretacea* specimen.

Recent studies by other workers (E. Puceat, written comm. 2003; S. Cumbaa, written comm. 2004) have included oxygen isotopic analysis of local samples of fish teeth and turtle bone obtained from the CSU collections, and these data are incorporated into this study. The samples include two *Enchodus* (Osteichthyes) teeth (KM02 and KM03), three *Squalicorax kaupi* (Selachii) teeth (KB06, KB07, and KB08), and two samples of bone from the marine turtle *Bothremys barberi* (CSU-K-81-03 and CSU-K-81-02). The two *Enchodus* teeth were collected from the Arcola Member of the Mooreville Formation in Dallas County, Alabama, which is equivalent to the upper Blufftown Formation in western Georgia. As for the shark teeth: Kb06 was collected from Hatchechubbee Creek in Russell County, Alabama; Kb07 was collected from the Sim's Hill locality, near Union Springs in Bullock County, Alabama, and Kb08 was collected from the Blufftown Formation, Hannahatchee Creek in Stewart County, Georgia. The turtle bone samples were also collected from Hannahatchee Creek in Stewart County, Georgia. The turtle bone and shark teeth samples also represent the early Campanian age.

Three carbonate samples were analyzed by Geochron Laboratories for strontium isotope ratios: one *E. upatoiensis* (KE05) specimen from Broken Arrow Bend, one *C. cusseta* specimen (KC04) from Hannahatchee Creek, and one *E. ponderosa* specimen (KB02) from an outcrop of the early Campanian-age Blufftown Formation along Hatchechubbee Creek in Russell County, Alabama.

Faunal analysis and paleoecology

Theory

INTRODUCTORY STATEMENT

Paleoecological analysis involves deriving ecological information from extant taxa and applying it to their fossil counterparts. Analysis of diversity, paleocommunity structure, and paleoecology of taxa are some of the methods used for reconstructing environmental parameters, and will be described in more detail in the following sections. Each of these methods of paleoecological analysis is not without limitations; however, an integrated approach will provide relatively reliable means to interpret results.

COMMUNITY ANALYSIS

A marine benthic paleocommunity consists of taxa that had similar habitat requirements controlled by a variety of environmental parameters, including available oxygen, substrate, current energy level, and salinity. Scott (1974, 1976) developed the idea, which has been supported by other studies (Bottjer, 1981;Fürsich and Kirkland, 1986; Bernasconi and Stanley, 1993; Hudson et al. 1995; Daley, 2002; Zuschin and Stanton, 2002; Henderson, 2004), that the structural aspects of ancient communities could be related to different depositional environments. Fossil faunal associations, (recurring suites of taxa) provide a starting point for the interpretation of Cretaceous paleocommunities because they tend to be found in characteristic lithofacies. This is an indication that the environment, particularly the substrate, influenced community development. Molluscs are among the most abundant marine invertebrates in the fossil

record and, in general, are very useful for paleoecological analysis because most are sensitive to environmental conditions. Bivalve molluscs, in particular, are especially useful for paleoenvironmental reconstruction because they are a common, ecologically varied class, and can be reliably grouped by their relationship to substrate, feeding habits, modes of attachment, and locomotion.

Substrate is an important environmental factor directly influencing specific bivalve life habits (i.e., infaunal, epifaunal, or reclining; shallow- vs. deep-burrowing) and feeding modes (i.e., suspension vs. detrital). For instance, trophic proportion (the proportion of deposit-feeding and suspension-feeding molluscs) has been widely used in paleoecology (Scott, 1976; Dodd and Stanton, 1991; Bernasconi and Stanley, 1993; Hudson et al., 1995), based on correlations between trophic structure and environmental conditions in modern communities. Deposit-feeding molluscs are most common on substrates with an abundance of accumulated organic material. These form in environments where water turbulence is low, and therefore where the sediment is fine-grained. Such conditions are more common in deep water, below the fair-weather storm wave base, but may also be found in protected shallow settings. Suspension-feeders, which feed by passing water with suspended food through the mantle cavity, are more abundant in turbulent water conditions, where food particles remain in suspension and, consequently, sediments are coarse-grained (Stanley, 1970). Cemented- and byssally-attached bivalves (e.g., oysters and mussels) usually require a hard substrate and are more common in areas with turbulent water, whereas burrowers need a soft substrate.

Faunal composition of a paleocommunity can also provide general information about salinity, especially fluctuating salinity. Fürsich (1993) discussed how to recognize salinity-controlled benthic associations and suggested that salinity-controlled benthic macroinvertebrate associations could be used to reconstruct salinity regimes of paleoenvironments. For example, the presence of mostly stenohaline organisms, such as the articulate brachiopods, calcareous sponges, corals, echinoderms, and cephalopods, and the bivalves *Ceratomya, Pholadomya, Inoceramus,* and *Barbatia,* would indicate fully marine conditions. Conversely, an assemblage with dominance of euryhaline taxa, such as the inarticulate brachiopod *Lingula*, boring clionid sponges, and the bivalves *Bakevellia*, *Protocardia*, as well as the neomiodontid bivalves, along with absence or scarcity of stenohaline taxa would suggest that salinity deviated from normal marine values, as in a brackish or hypersaline environment (Fürsich 1993; Fürsich et al. 1995).

FAUNAL DIVERSITY

Diversity is a measure of the complexity of a community and is related to the degree of environmental stress experienced by the community. Abiotic stressors can include fluctuating salinity, wave action, unstable substrate, and low available oxygen. Generally, high stress environments are characterized by low diversity communities with a simple trophic structure, whereas low stress environments support high diversity communities that have a more complex trophic structure. This generalized relationship holds true in modern environments where salinity is the dominant factor and, with consideration for potential problems, can be applied to the fossil record to analyze ancient

paleosalinities (Fursich, 1993; Fursich et al., 1995). Remane (1958 *in* Fürsich 1993) showed that in the Recent a diversity minimum exists around 5‰ salinity, above which most freshwater species cannot exist and only very few marine species can tolerate the abnormally low salinity. He also showed that diversity increases away from the species minimum toward the freshwater end and toward the marine end of the salinity range. However, other environmental stress factors, which may also influence diversity must be evaluated, including temperature and low oxygen.

Methods

Paleoecological reconstructions for this study were based on both published and unpublished faunal surveys of the Late Cretaceous Chattahoochee River Valley region (Veatch and Stephenson, 1911; Stephenson 1914; Vickers, 1967; Schwimmer 1986) to provide a database of known taxa. A thorough taxonomic revision (Moore, 1969; Akers and Akers, 2002) was necessary for the earlier faunal surveys, since many of the generic names used by Stephenson are now invalid. Paleoecological characteristics have been inferred from phylogeny and functional morphology, including feeding habits, substrate niche relations, and life modes of the taxa (Stanley, 1970; Thomas, 1978; Dodd and Stanton, 1991; Beesley et al., 1998; Neogene Marine Biota of Tropical America database; The Paleobiology Database). Diversity, trophic proportions, and life habit proportions were determined for 26 Late Cretaceous localities with the aid of tables constructed using Excel, and the results of seven of these localities are detailed in the following section.

RESULTS AND DISCUSSION

Paleobotanical Analysis

The Santonian-age deposits of the region under study are the only ones which contain enough plant material to provide an adequate sample size for leaf margin analysis (LMA), which is therefore restricted to that age. Terrestrial mean annual temperature (MAT) of the Santonian Gulf Coastal Plain is graphed in Figure 4, based on paleobotanical data. On this graph, mean annual temperature is plotted against the percentage of entire-margined leaves using three different mean annual temperature scales: two devised for the northern hemisphere by Wolfe (1979) and Wilf (1997), and a third, the southern hemisphere scale of Wolfe and Upchurch (1987). The Southern Hemisphere scale is considered to be a more accurate scale for the Southeastern United States during the Late Cretaceous, based on similarities between Late Cretaceous assemblages and the assemblages typical of the modern Southern Hemisphere. Modern vegetation in the Southern Hemisphere has a higher percentage of entire-margined species relative to temperature than does the Northern Hemisphere. Wolfe and Upchurch (1987) suggested that this was probably due to the near-absence of deciduous plants in the Southern Hemisphere at the time, as well as to the common occurrence of conifers, not unlike the composition typical of Late Cretaceous assemblages.

As in the Northern Hemisphere, Wolfe's (1979) data from the Southern Hemisphere indicates that mean annual temperature correlates with leaf margin type. The relationship between the two parameters is an approximate 3% increase in entire-margined species per

1°C increase in temperature in the Northern Hemisphere, whereas the relationship is about 4 % / °C in the Southern Hemisphere. For this reason, the Southern Hemisphere scale yields more conservative estimates of temperature than do the other two scales.

The proportion of entire vs. non-entire margins in angiosperm taxa from the Santonian-age Eutaw Formation in Alabama and Georgia was calculated to be 96.2 percent. The equations for the linear regressions, where **MAT** is mean annual temperature (°C), and **P** is percent taxa with entire margins, in this case .962, are as follows:

Wolfe (1979):

$MAT = 30.6\,P + 1.14$

$MAT = 30.6\,(.962) + 1.14 =$ **30.6 °C**

Wilf (1997):

$MAT = 28.6\,P + 2.24$

$MAT = 28.6\,(.962) + 2.24 =$ **29.8 °C**

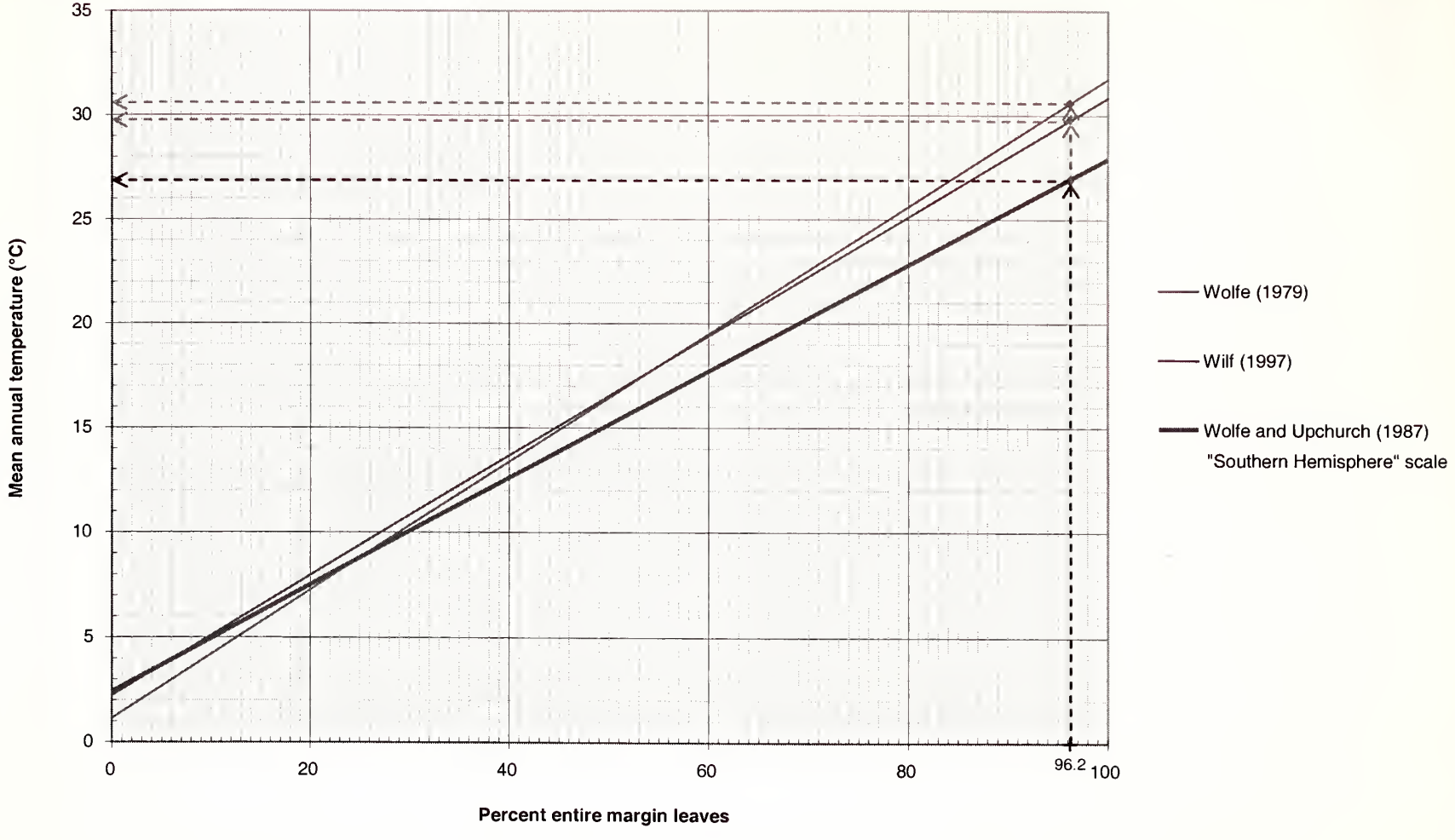
Wolfe and Upchurch (1987):

$MAT = 25.5\,P + 2.41$

$MAT = 25.5\,(.962) + 2.41 =$ **26.9 °C**

The Santonian Age of the Late Cretaceous Epoch was characterized by exceedingly warm temperatures (Wolfe and Upchurch, 1987; Frakes, 1999). Results of this analysis, using the more conservative Southern Hemisphere scale of Wolfe and Upchurch (1987), indicate a terrestrial mean annual temperature of ~27 °C. This temperature is consistent with the results of Wolfe and Upchurch's (1987) comprehensive analysis of North American terrestrial climates during the Late Cretaceous. Some caution must be exercised when interpreting this analysis: one cannot be certain that a particular fossil flora is a representative sample of total ancient vegetation of which it was a part. In fact, Berry (1919) pointed out that the Eutaw flora is not truly representative of the flora of the Santonian Age because most of the plant remains had undergone considerable maceration, with only the more coriaceous forms preserved. However, this analysis is not meant to stand alone, but to be used to supplement and corroborate conclusions derived from other lines of evidence.

Figure 4: Results of Leaf Margin Analysis



Geochemical Analysis

Geochemical data obtained from macrofossil samples for this study are shown in Table 3. The carbonate $\delta^{18}O$ values for the Santonian range from -2.43‰ to -3.70‰ with a mean value of -3.0‰. Samples from the early Campanian show a range of values from -2.92‰ to -1.95‰ with a mean of -2.48‰. Late Campanian $\delta^{18}O$ values range between -4.15‰ and -3.31‰ with a mean of -3.53‰. These values are in general agreement with those of other studies that have analyzed carbonate $\delta^{18}O$ data from the middle latitudes (~30°N - 40°N) of the Late Cretaceous (Spicer and Corfield, 1992; Frakes, 1999; Yildiz and Ozdemir, 1999; Pearson et al., 2001; Moriya et al., 2003; Immenhauser et al., 2005)

Paleotemperatures were calculated from the carbonate $\delta^{18}O$ values using the equation of Anderson and Arhtur (1983 *in* Fassell and Bralower, 1999), devised specifically for use with bivalves:

$$T(°C) = 16.0 - 4.14(\delta_c - \delta_w) + 0.13(\delta_c - \delta_w)^2$$

where δ_c is the $\delta^{18}O$ value of the carbonate sample relative to the PeeDee Belemnite (PDB) standard and δ_w is the assumed $\delta^{18}O$ value of Late Cretaceous seawater, relative to SMOW (standard mean ocean water). Accuracy of paleotemperature estimates is highly dependent on the use of the correct value for δ_w. Average modern seawater δ_w is standardized as 0.0‰. Many studies of Late Cretaceous paleoclimate assume a δ_w of -1.0‰ for a presumed ice-free Late Cretaceous world. However, some authors (Shackleton, Corfield, and Hall, 1985; Spicer and Corfield, 1991; Zacke et al., 2004; Immenhauser, et al., 2005) suggest a value of -0.5‰ for lower latitudes, reflecting both the assumed lack of polar ice caps (-1.2‰) and surface water depletion of approximately

-0.7‰ due to effects of evaporation at lower latitudes. For this study, a δ_w of -0.5‰ is assumed.

The estimated mean paleotemperatures calculated from carbonate oxygen isotope data are 26.8° C for the Santonian, 23.5° C for the early Campanian, and 28.2° C for the late Campanian. Oxygen isotope data are scarce for the Santonian and Campanian ages of the Late Cretaceous in general, and for the middle latitudes in particular. Most paleoclimate work has focused on the mid-Cretaceous (Turonian) thermal maximum, the end-Cretaceous (K-P boundary), and/or on the high latitudes. Paucity of data notwithstanding, the results of this study reflect the trend shown in other available paleoclimate studies of the Late Cretaceous (Schönfeld et al., 1991; Huber et al., 1995; Huber 1998; Norris et al., 2001; Skelton, 2003 *in* Skelton et al, 2003). The paleoclimate trend demonstrates that maximum warmth occurred in the Turonian, followed by very gradual cooling, with fluctuations, through the Late Cretaceous with another, smaller warming trend in the late Campanian, followed by cooling into the Maastrichtian. The results of this study also show warm paleotemperatures in the Santonian, somewhat cooler temperatures in the early Campanian, followed by considerably warmer paleotemperatures in the mid- to late-Campanian.

Paleotemperature estimates based on phosphatic bone and tooth samples were calculated using the equation of Kolodny et al. (1983 *in* Kolodny and Luz, 1991):

$$T(°C) = 113.3 - 4.38(\delta_p - \delta_w)$$

where δ_p is the $\delta^{18}O$ value of the phosphate sample relative to SMOW. The paleotemperature estimates from the shark tooth enamel and turtle bone data are somewhat lower than those calculated from the contemporaneous early Campanian carbonate samples, but not unreasonably so, ranging from 19.7° C to 24.4° C, the mean being 22.7° C. The paleotemperature estimates from the *Enchodus* teeth, however, are anomalously low, 17.6° C. This can be explained in part by the environment of the species involved. The salmoniform fish genus *Enchodus* is considered to have been active mid-water or pelagic predators which probably migrated between cooler and warmer waters. In fact, these samples were collected from the Mooreville Formation in western Alabama, representative of an open-marine carbonate shelf paleoenvironment. Other studies of phosphatic isotope data (Skelton, 2003 in Skelton et al., 2003; Zacke et al., 2004) have shown that estimated paleotemperatures derived from marine vertebrates known to inhabit deeper, offshore waters are considerably lower than those from contemporaneous bivalves from shallower shelf seas. Additionally, oxygen isotope analysis of samples obtained from a fossil coelacanth (Kolodny and Luz, 1991) from the same locality as the *Enchodus* specimens were identical to the *Enchodus* results. The low temperatures calculated from these two samples probably reflect the cooler temperatures of a deeper open-marine environment.

Table 1: Geochemical analysis of Late Cretaceous macrofossils

Age	Sample	87Sr/86Sr	δ13C	δ180-SMOW	δ180-PDB	T(°C)δw =-0.5	Specimen
Late Campanian	Kc1	0.707501					
	Kc2		-1		-3.31	28.3	
	Kc3		-0.9		-3.50	29.2	*Crassostrea cusseta*, from Hannahatchee Cr.
	Kc4		-0.45		-4.15	31.1	
	Kc5		-0.54		-3.30	27.6	
	Kc6		-1.1		-3.38	27.9	
Early Campanian	Km1		-1.1		-3.21	27.9	Mooreville chalk sample (from *Deinosuchus* tooth)
	Km2			21.4		17.4	*Enchodus* tooth from Dallas Co., AL
	Km3			21.3		17.8	*Enchodus* tooth from Dallas Co., AL
	Kb2		-0.9		-2.92	26.5	
	Kb3		1.2		-1.95	22.1	
	Kb4		0.15		-2.60	24.7	
	Kb5		0.29		-2.43	24.0	*Exogyra ponderosa*, from Hitchitee Cr.
	Kb6		-0.7		-2.82	26.0	
	Kb7		1.27		-2.46	24.1	
	Kb8		1.29		-2.18	23.0	
	Kb9	0.707473					
	Kb10			19.8		24.4	*Squalicorax kaupi* fr. Hatchechubbee Cr.
	Kb11			20.9		19.7	*Squalicorax kaupi* fr. Sim's Hill locality, Bullock Co., AL
	Kb12			19.9		23.9	*S. kaupi* fr. Hannahatchee Cr.
	Kb13			20.0		23.5	*Bothremys barberi* fr. Hannahatchee Cr.
	Kb14			20.4		21.8	*Bothremys barberi* fr. Hannahatchee Cr.
Santonian	Ks1		-5.5		-3.31	28.3	
	Ks2		2.36		-2.77	25.4	
	Ks3		1.74		-2.96	26.2	*Ostrea cretacea*, from Upatoi Cr.
	Ks4		-7.39		-3.24	27.3	
	Ks5		1		-3.70	30.2	
	Ks6		1.1		-2.43	24.3	
	Ks7		1.2		-2.63	25.2	*Exogyra upatoiensis*, from Broken Arrow Bend
	Ks8	0.707341					

Carbonate $\delta^{13}C$ values for the Santonian are highly variable, and range from -7.39‰ to 2.36‰. The values for samples Ks1 (-5.5‰) and Ks4 (-7.39‰) are so anomalously low that they are certainly unreliable, probably the result of groundwater alteration of the original carbon isotope ratio. Although carbon isotope ratios of carbonates are less susceptible to diagenesis than are oxygen isotope ratios, they may nevertheless be subject to certain effects of the local organic carbon balance, such as local productivity and/or decay of organic matter. Excluding these two samples, the $\delta^{13}C$ values for the Santonian are still quite variable, ranging from 1.0‰ to 2.36‰, with a mean value of 1.48‰. Early Campanian values show even more variability than those from the Santonian, and range from -1.1‰ to 1.29‰ with a mean of 0.19‰. Samples from the late Campanian show much less spread, with a range between -1.1‰ and -0.45‰, and a mean value of 0.80‰. It is noteworthy that the $\delta^{13}C$ and $\delta^{18}O$ data for the early Campanian show strong positive covariance, which is considered evidence of "brackish" water conditions by Hendry et al. (2001); the pattern for the Santonian and the late Campanian data is less discernible, in part as a result of the variability of the data.

All $\delta^{13}C$ data are plotted on the paleosalinity scale of Yin (1991) in Figure 5. Salinity regimes are subdivided into hyperhaline, euhaline, "brackish" (polyhaline, mesohaline, and oligohaline), and freshwater following the classification system used by the U.S. Fish and Wildlife Service (Table 4). All of the data obtained for this study show generally "brackish" salinity values. Based on the paleosalinity scale, the samples from the Santonian reflect paleosalinity values ranging between 26 and 33 ‰, and fall well within the upper brackish polyhaline salinity regime. Both early Campanian and late Campanian

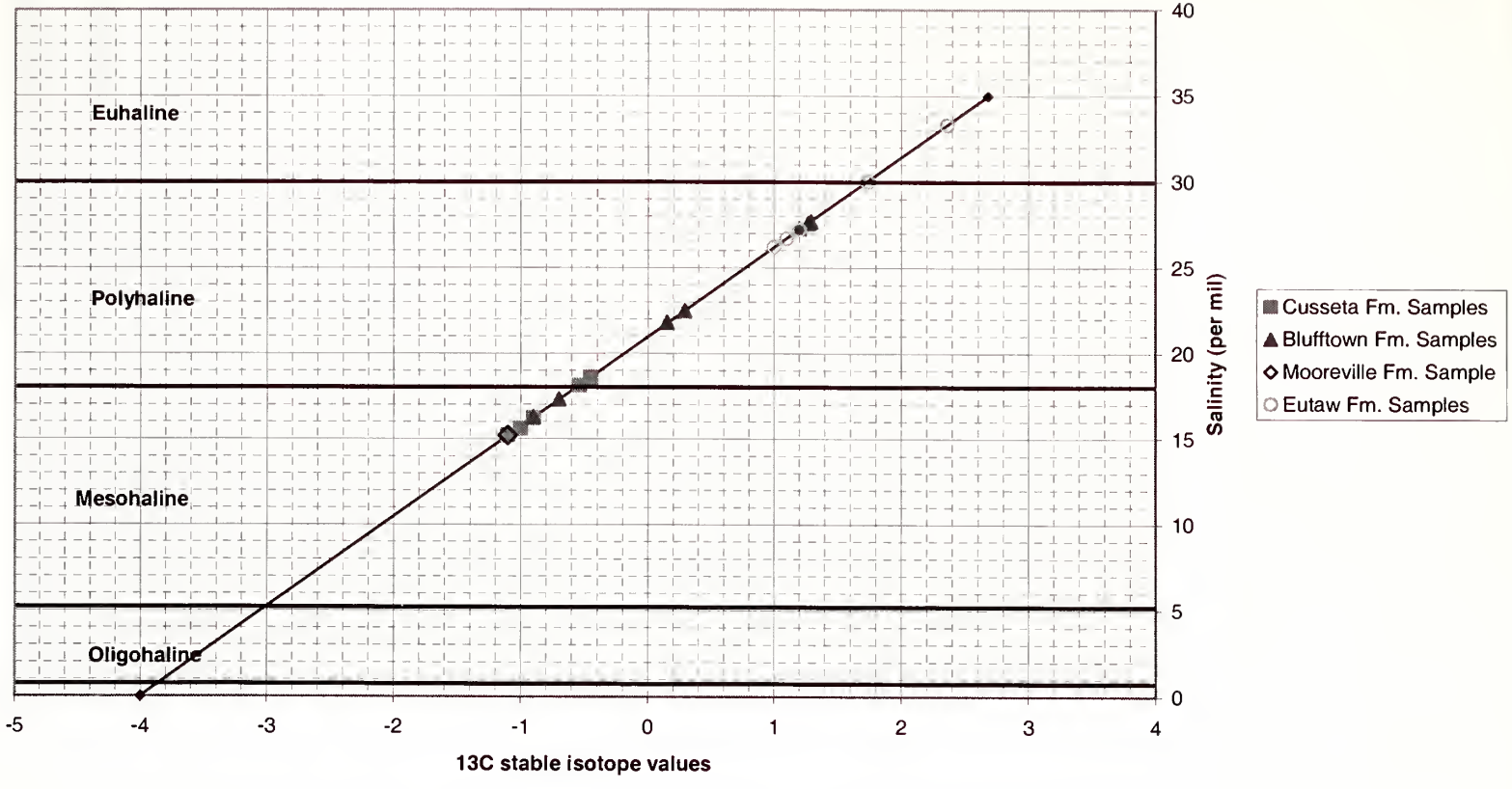
data reflect upper mesohaline to polyhaline values, ranging from 15 to 27 ‰, and 15 to 21.5 ‰, respectively. The precise relationship between carbon isotope values and salinity is quite complex, and must take into account such variables as temperature, productivity, and source of carbon in dissolved bicarbonate. The interpretation here, therefore, should be regarded only as approximate.

Table 4: Salinity classification

Coastal Modifiers	Salinity (parts per thousand)
Hyperhaline	>40
Euhaline	30.0 – 40.0
Mixohaline (Brackish)	0.5 – 30.0
Polyhaline	18.0 – 30.0
Mesohaline	5.0 – 18.0
Oligohaline	0.5 – 0.5
Fresh	<0.5

Modified from U.S. Fish and Wildlife Classification of Wetlands and Deepwater Habitats

Figure 5: Paleosalinity scale based on stable carbon isotope ratios



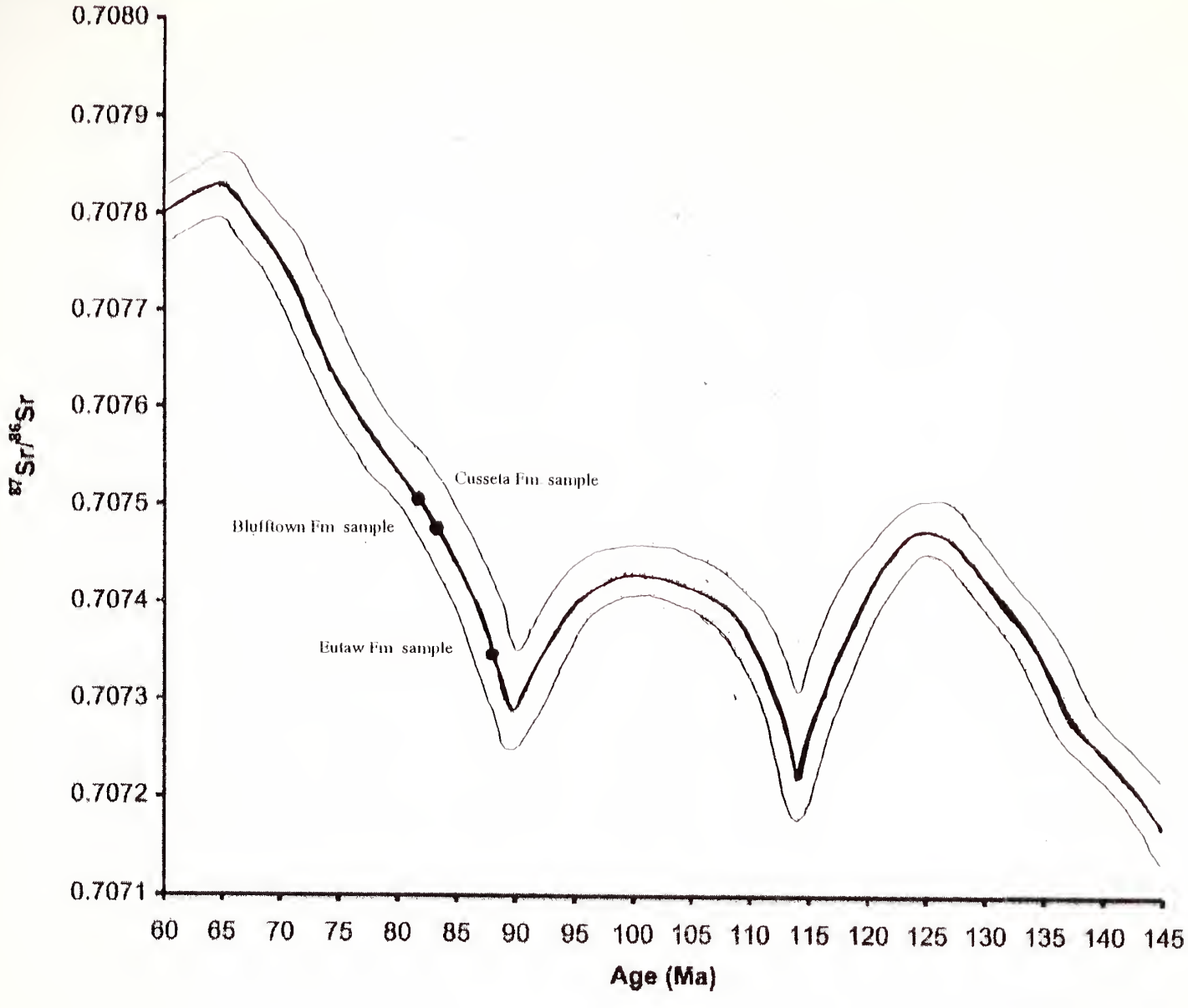
Strontium isotope analysis was too cost-prohibitive for more than a few samples (a total of three – one from each stage), too few to provide definitive information about paleosalinity and/or geologic age. However, the results can serve as a precursory examination into their potential usefulness for distinguishing between marine and non-marine environments, as well as for Sr-isotope stratigraphy. The $^{87}Sr/^{86}Sr$ ratios are 0.707341 for the sample obtained from the Eutaw Fm, 0.707473 for the Blufftown Formation sample, and 0.707501 for sample from the Cusseta Formation. Marginal marine paleosalinities may be determined from $^{87}Sr/^{86}Sr$ ratios if the seawater and freshwater end members are known (Schmitz et al., 1991; Holmden et al., 1997; Cochran et al., 2002). The marine end member can be estimated from the global Late Cretaceous $^{87}Sr/^{86}Sr$ seawater evolution curve of McArthur et al. (1994) shown in Figure 6; however, the main source of uncertainty is in the estimation of the basin-specific freshwater concentration. The strontium isotope ratio of river water (and groundwater) draining into coastal areas reflects the isotopic composition of the bedrock in the drainage area. Freshwaters draining from old cratonic regions dominated by Rb-rich granitic rocks have $^{87}Sr/^{86}Sr$ ratios ranging from 0.715-0.740, whereas $^{87}Sr/^{86}Sr$ values of freshwaters flowing from regions with calcite-rich rocks range from as low as 0.704 to 0.708 (Schmitz et al. 1991). Due to the limitations of this study, the $^{87}Sr/^{86}Sr$ ratio of the freshwater end member cannot be defined; therefore, paleosalinity cannot be reliably estimated with this method. However, general observations can be made. The sample from the Blufftown Formation has a $^{87}Sr/^{86}Sr$ value that falls within the expected range of values (0.70746 – 0.70755) for normal marine seawater at approximately 82 Ma. The

Eutaw Formation sample is lower than marine values, and the sample from the Cusseta Formation is slightly lower than expected. In their study of strontium isotope ratios and paleosalinity in the Maastrichtian WIS, Cochran et al. (2002) observed progressively lower $^{87}Sr/^{86}Sr$ values from offshore (marine) to brackish facies. It should be noted that they reported a "significant" difference ($\sim 1.6 \times 10^{-4}$) between open-ocean values and brackish values. The Eutaw Formation sample from this study shows a difference of about 8.0×10^{-5}, a much smaller difference from the expected marine value than that observed by Cochran et al (2002), therefore, the paleosalinity may have been only slightly less than fully marine, that is the "upper brackish" polyhaline regime.

Regarding geologic age determination, the values obtained here are generally compatible with data reported in other studies (see Figure 6). With reference to the composite Sr-isotope stratigraphic curve of McArthur et al. (1994), the Eutaw Formation sample corresponds to a geologic age of about 88 million years (± 2 m.y.), the Blufftown sample to about 84 million years (± 2 m.y.), and the Cusseta Formation sample to about 82 million years (± 3 m.y.). If reliable, these values, (especially the Cusseta Formation sample) represent older geologic ages than those to which the Santonian and Campanian Formations have been assigned. Whether this is because the current age assignments of the Santonian and Campanian Formations are inaccurate, or because salinity values deviated from fully marine seawater, cannot be determined with the small sample size in this study. More extensive sampling and strontium isotope analyses of the regional Late Cretaceous strata would be worthwhile in order to provide a larger database of samples

for paleosalinity analysis, to refine formational ages in this region, and to add to the global database, particularly for the Campanian Stage.

Figure 6: Strontium isotope stratigraphic curve (modified from McArthur et al., 1994)



Paleoecological Analysis

This section describes the paleoecology of molluscs from selected localities most representative of the Eutaw, Blufftown, and Cusseta Formations. As mentioned previously, the Broken Arrow Bend, Blufftown, and Florence sites along the Chattahoochee River are no longer accessible as a result of the construction of the dam at Ft. Gaines, Georgia.

Eutaw Formation Localities

OCHILLEE CREEK

Represented by 32 molluscan species (Table 5), this high diversity assemblage was characterized by several euryhaline species including four corbulids, several oysters, as well as *Anomia preolmstedi, Cymbophora lintea, Trachycardium ochilleanum, Nucula percrassa,* and *Pseudoptera securiformis.* Bivalves comprised 84% of the molluscan fauna, followed by gastropods (9%) and cephalopods (6%), including the unusual heteromorph ammonite *Turrilites.* Among bivalves, more than 96% were suspension feeders, and 52% were infaunal. Modern corbulids and mactridids are a common component of estuaries and embayments, with high tolerance of environmental instability, particularly fluctuating salinity levels. The presence of several presumably marine-stenohaline taxa (*Pinna, Placenticeras,* and *Turrilites*) in association with abundant taxa known to characterize brackish water environments suggests near normal salinities in the upper polyhaline to euhaline range. The environment may have been a

bay or lagoon in communication with the open sea. Alternatively, this assemblage may represent time-averaging, which led to mixing of different community relicts.

UPATOI CREEK

Seventeen species are in this moderately diverse assemblage (Table 6). Among the bivalves, which account for 71% of all the molluscan species, 58% are infaunal, and 83% are suspension feeders. Apart from the ammonite *Placenticeras benningi*, gastropods account for the rest (24%). Several euryhaline bivalve forms are present, among them *Exogyra upatoiensis*, *Ostrea cretacea*, *Nuculana sp.,*and *Caryocorbula oxynema.* Selachians are represented by *Scapanorhynchus texanus*, *Squalicorax falcatus, Cretolamna appendiculata.*, and *Cretodus simplicatus.* In this assemblage, the marine-stenohaline *Pholadomya* and *Placenticeras benningi* occur together with several euryhaline species. Corbulids and oysters are common elements of polyhaline environments; however, their wide environmental tolerances enabled them to live in fully marine conditions. The high species richness of this community, which is characterized by several shallow and/or slow burrowing forms, indicates relatively stable, low-stress conditions. The $\delta^{13}C$ values indicate near-normal marine salinity values ranging from upper polyhaline to euhaline (26-33 ppt). The assemblage occurred in very fine-grained, dark greenish-gray argillaceous clay with discontinuous nodular limestone layers and irregularly distributed lime concretions with scattered fragments of lignite (Stephenson, 1956). This sediment type, along with the presence of several detritus-feeding species of

gastropods and the deposit-feeding clams *Tellina* and *Nuculana*, indicates that the assemblage apparently lived in a low energy environment.

BROKEN ARROW BEND

This paleocommunity is represented by 13 molluscan species (Table 7). Bivalves represent 85% of the taxa, with *Ostrea cretacea* the dominant species; one gastropod species, and one cephalopod species each represent 8% of the molluscan fauna. Among bivalves, 100% were suspension feeders, and epifaunal forms account for 45% of the species. Representative bivalve taxa include *Perna sp., Exogyra upatoiensis, Cardium sp., Caryocorbula oxynema,* and *C. veatchi.* Other common taxa include the selachians *Scapanorhynchus texanus* and *Cretolamna appendiculata.* Fossil leaves have also been collected from this locality, and include *Malapoenna horrellensis* (a member of the Laurel family), *Sequoia reichenbachi, Salix eutawensis, S. flexuosa,* and the reed *Phragmites pratti.* The dominance of taxa which characterize reduced salinity environments, and the somewhat low species richness, identify this as a brackish, polyhaline environment. This agrees well with the $\delta^{13}C$ values obtained from the *Exogyra upatoiensis* specimens, which indicate the upper polyhaline regime (~26 ppt). This assemblage occurred in finely arenaceous, slightly laminated clay, which, along with the presence of fossil leaves, suggests a low-energy, nearshore environment, possibly the shallow mud flats of an estuary in the vicinity of a coastal swamp.

Table 5: OCHILLEE CREEK MOLLUSCS
(From Veatch and Stephenson, 1911; Stephenson, 1914)

Class	Species	Substrate relationship	Trophic level
Bivalve	*Anomia preolmstedi*	epifaunal	suspension feeder
Bivalve	*Legumen carolinense*	infaunal	suspension feeder
Bivalve	*Breviarca? (=Striarca) symmetros*	semi-infaunal	suspension feeder
Bivalve	*Trachycardium ochilleanum*	infaunal	suspension feeder
Bivalve	*Corbula carolinensis (=?Caryocorbula oxynema)*	infaunal	suspension feeder
Bivalve	*Crassatellites? (=Crassatella)*	infaunal	suspension feeder
Bivalve	*Cucullaea (=Idonearca) sp.*	infaunal	suspension feeder
Bivalve	*Cymbophora lintea*	infaunal	suspension feeder
Bivalve	*Cyprimeria depressa*	infaunal	suspension feeder
Bivalve	*Etea carolinensis*	infaunal	suspension feeder
Bivalve	*Glycymeris sp.*	~epi/infaunal	suspension feeder
Bivalve	*Leptosolen biplicata*	infaunal	suspension feeder
Bivalve	*Nucula percrassa*	infaunal	deposit feeder
Bivalve	*Ostrea cretacea*	epifaunal	suspension feeder
Bivalve	*Camptonectes sp.*	epifaunal	suspension feeder
Bivalve	*Perna sp. nov.*	semi-infaunal	suspension feeder
Bivalve	*Trigonarca inflata*	semi-infaunal	suspension feeder
Bivalve	*Caryocarbula georgiana*	infaunal	suspension feeder
Bivalve	*Caryocorbula longi*	infaunal	suspension feeder
Bivalve	*Caryocorbula? veatchi*	infaunal	suspension feeder
Bivalve	*Cymbophora ochilleana*	infaunal	suspension feeder
Bivalve	*Exogyra upatoiensis*	epifaunal	suspension feeder
Bivalve	*Gryphaea wratheri (=Pycnodonte aucella)*	epifaunal	suspension feeder
Bivalve	*Ostrea (Lopha) ucheensis*	epifaunal	suspension feeder
Bivalve	*Protarca obliqua*	semi-infaunal	suspension feeder
Bivalve	*Pseudoptera securiformis*	epifaunal	suspension feeder
Bivalve	*Pinna sp.*	semi-infaunal	suspension feeder
Gastropod	*Anchura sp.*	infaunal	deposit/suspension feeder
Gastropod	*Turritella vertebroides*	infaunal	suspension feeder
Gastropod	*Anomalofusus substriatus*	epifaunal	carnivore
Cephalopod	*Placenticeras benningi*	nektonic	carnivore
Cephalopod	*Turrilites? sp.*	nektonic	carnivore

Table 6: UPATOI CREEK MOLLUSCS
(From Veatch and Stephenson, 1911; Stephenson, 1914)

Class	Species	Substrate relationship	Trophic level
Bivalve	*Leda (=Nuculana)sp. nov.*	infaunal	deposit feeder
Bivalve	*Cucullaea ?*	infaunal	suspension feeder
Bivalve	*Perna sp. nov.*	semi-infaunal	suspension feeder
Bivalve	*Ostrea cretacea*	epifaunal	suspension feeder
Bivalve	*Exogyra upatoiensis*	epifaunal	suspension feeder
Bivalve	*Pholadomya sp. nov.*	infaunal	suspension feeder
Bivalve	*Cardium sp.*	infaunal	suspension feeder
Bivalve	*Baroda (=Legumen) carolinense*	infaunal	suspension feeder
Bivalve	*Corbula carolinensis (=Caryocorbula oxynema)*	infaunal	suspension feeder
Bivalve	*Pseudoptera securiformis*	epifaunal	suspension feeder
Bivalve	*Trigonarca sp.*	semi-infaunal	suspension feeder
Bivalve	*Tellina sp.*	infaunal	deposit/suspension feeder
Gastropod	*Turritella sp.*	infaunal	suspension feeder
Gastropod	*Anchura sp.*	infaunal	deposit/suspension feeder
Gastropod	*Volutomorpha sp.*	epifaunal	carnivore
Gastropod	*?Acmaea sp.*	epifaunal	grazer
Cephalopod	*Placenticeras benningi*	nektonic	carnivore

Table 7: BROKEN ARROW BEND MOLLUSCS
(From Veatch and Stephenson, 1911; Stephenson, 1914)

Class	Species	Substrate relationship	Trophic level
Bivalve	*Perna sp.nov.*	semi-infaunal	suspension feeder
Bivalve	*Ostrea cretacea*	epifaunal	suspension feeder
Bivalve	*Exogyra upatoiensis*	epifaunal	suspension feeder
Bivalve	*Pecten sp.*	epifaunal	suspension feeder
Bivalve	*Anomia preolmstedi*	epifaunal	suspension feeder
Bivalve	*Cardium sp.*	infaunal	suspension feeder
Bivalve	*Cyprimeria sp.*	infaunal	suspension feeder
Bivalve	*Baroda (Legumen) carolinense*	infaunal	suspension feeder
Bivalve	*Corbula carolinensis (=Caryocorbula oxynema)*	infaunal	suspension feeder
Bivalve	*Pseudoptera securiformis*	epifaunal	suspension feeder
Bivalve	*Caryocorbula veatchi*	infaunal	suspension feeder
Gastropod	*Turritella sp.*	epifaunal	suspension feeder
Cephalopod	*Placenticeras benningi*	nektonic	carnivore

Blufftown Formation Localities

BLUFFTOWN

The assemblage collected from the Blufftown Formation type locality, formerly exposed along the bluffs of the Chattahoochee River in Stewart County, was a complex, high diversity community, with 69 molluscan species (Table 8). Bivalves dominated the fauna (78%), but gastropods (14%), cephalopods (5%), and scaphopods (3%) were also included. Among the bivalves, 57% were infaunal, and 90% were suspension feeders. The protobranch deposit-feeders, however, were well-represented at this locality by *Nucula percrassa, N. eufalensis, Nuculana pittensis*, and *N. protexta*; the two scaphopod species are also (microcarnivorous) deposit feeders. Euryhaline bivalves included several corbulid species, several oyster species, *Scabrotrigonia eufalensis, Anomia argentaria, A. preolmstedi, Cymbophora subtilis,* and *Perna sp.* Although numerous euryhaline bivalve species are present, the occurrence of the comparatively stenohaline *Inoceramus sp.*, *Barbatia lintea*, and several pectens, along with the very high species richness suggests that salinity probably did not vary much from normal marine values. *Scapanorhynchus texanus*, bony fish vertebrae, crab claws, and the serpulid worms *Serpula sp.,* and *Hamulus major*, were among other fossils collected from this site. The association occurred in calcareous fine sand and sandy clay (Stephanson, 1956) which, along with the high diversity faunal composition dominated by suspension feeders (typically most abundant in turbulent water conditions) suggests a subtidal, nearshore environment within influence of wave action.

HITCHITEE CREEK

The Hitchitee Creek locality contains a paucispecific molluscan association consisting primarily of abundant *Exogyra ponderosa* (Table 9). The strong dominance of *E. ponderosa*, a euryhaline species capable of thriving in brackish water environments, and the extremely low diversity assemblage, suggest adverse environmental conditions which excluded most other organisms. Carbon isotope ratios obtained from *E. ponderosa* specimens from this site indicate salinity values ranging from 16-28 ‰, suggesting that fluctuating salinity appears to have been the main stress factor in a mid- to outer estuarine environment.

Table 8: BLUFFTOWN MOLLUSCS
(From Veatch and Stephenson, 1911; Stephenson, 1914)

Class	Species	Substrate relationship	Trophic level
Bivalve	*Nucula percrassa*	infaunal	deposit feeder
Bivalve	*Nucula eufalensis*	infaunal	deposit feeder
Bivalve	*Leda (=Nuculana) pittensis*	infaunal	deposit feeder
Bivalve	*Cucullaea (=Idonearca) carolinensis*	infaunal	suspension feeder
Bivalve	*Trigonarca sp.*	semi-infaunal	suspension feeder
Bivalve	*Perrisonota (=Nuculana) protexta*	infaunal	deposit feeder
Bivalve	*Breviarca (=Striarca) umbonata*	semi-infaunal	suspension feeder
Bivalve	*Breviarca (=Striarca) saffordi*	semi-infaunal	suspension feeder
Bivalve	*Nemodon sp. nov.*	semi-infaunal	suspension feeder
Bivalve	*Arca sp.*	epifaunal	suspension feeder
Bivalve	*Barbatia (Polynema) lintea*	epifaunal	suspension feeder
Bivalve	*Glycymeris? sp. nov.?*	semi-infaunal	suspension feeder
Bivalve	*Gervilliopsis (=Gervillia) ensiformis*	semi-infaunal	suspension feeder
Bivalve	*Perna sp. nov.*	semi-infaunal	suspension feeder
Bivalve	*Inoceramus sp.*	epifaunal	suspension feeder
Bivalve	*Pteria petrosa*	epifaunal	suspension feeder
Bivalve	*Ostrea plumosa*	epifaunal	suspension feeder
Bivalve	*Ostrea whitei*	epifaunal	suspension feeder
Bivalve	*Gryphaea (=Pycnodonte) sp.*	epifaunal	suspension feeder
Bivalve	*Exogyra ponderosa*	epifaunal	suspension feeder
Bivalve	*Trgonia (=Scabrotrigonia) eufalensis*	infaunal	suspension feeder
Bivalve	*Pecten (=Camptonectes) burlingtonensis*	epifaunal	suspension feeder
Bivalve	*Pecten argillensis (=Camptonectes bubonis)*	epifaunal	suspension feeder
Bivalve	*Pecten? (=Camptonectes) cliffwoodensis*	epifaunal	suspension feeder
Bivalve	*Pecten bellisculptus*	epifaunal	suspension feeder
Bivalve	*Lima? kerri*	epifaunal	suspension feeder
Bivalve	*Anomia argentaria*	epifaunal	suspension feeder
Bivalve	*Anomia preolmstedi*	epifaunal	suspension feeder
Bivalve	*Liopistha sp.*	infaunal	suspension feeder
Bivalve	*Veniella conradi*	infaunal	suspension feeder
Bivalve	*Etea carolinensis*	infaunal	suspension feeder
Bivalve	*Venericardia?*	infaunal	suspension feeder
Bivalve	*Crassatella carolinensis*	infaunal	suspension feeder
Bivalve	*Crassatellites (=Crassatella) roodensis*	infaunal	suspension feeder
Bivalve	*Arena (=Brachymeris) carolinensis*	infaunal	suspension feeder
Bivalve	*Lucina glebula*	infaunal	chemosymbiotic/deposit feeder
Bivalve	*Cardium (=Granocardium) alabamense*	infaunal	suspension feeder
Bivalve	*Cardium (=Pleuriocardia) eufaulense*	infaunal	suspension feeder
Bivalve	*Cardium (=Protocardia) spillmanii*	infaunal	suspension feeder
Bivalve	*Cardium (=Granocardium) dumosum*	infaunal	suspension feeder
Bivalve	*Cardium sp.*	infaunal	suspension feeder
Bivalve	*Isocardia (=Glossus)sp.*	infaunal	suspension feeder
Bivalve	*Cyprimeria depressa*	infaunal	suspension feeder
Bivalve	*Aphrodina regia*	infaunal	suspension feeder
Bivalve	*Aphrodina sp.*	infaunal	suspension feeder
Bivalve	*Cyclothyris (=Cyclorisma) alta*	infaunal	suspension feeder
Bivalve	*Legumen planulatum*	infaunal	suspension feeder
Bivalve	*Linearia carolinensis*	infaunal	suspension feeder
Bivalve	*Linearia sp.*	infaunal	suspension feeder
Bivalve	*Leptosolen biplicata*	infaunal	suspension feeder
Bivalve	*Schizodesma appressa (=Cymbophora subtilis)*	infaunal	suspension feeder
Bivalve	*Corbula (=Caestocorbula) crassiplica*	infaunal	suspension feeder
Bivalve	*Corbula carolinensis (=Caryoborbula oxynema)*	infaunal	suspension feeder
Bivalve	*Corbula sp.*	infaunal	suspension feeder
Scaphopod	*Dentalium ripleyanum*	infaunal	microcarnivorous deposit feeder
Scaphopod	*Cadulus obnutus*	infaunal	microcarnivorous deposit feeder
Gastropod	*Astralium?*	epifaunal	grazer
Gastropod	*Lunatia (=Euspira) obliquata*	epifaunal	carnivore
Gastropod	*Gyrodes sp.*	epifaunal	
Gastropod	*Turitella quadrilira*	infaunal	suspension feeder
Gastropod	*Turritella sp.*	infaunal	suspension feeder
Gastropod	*Turritella sp.*	infaunal	suspension feeder
Gastropod	*Pterocerella tippana*	epifaunal	

Table 8 continued			
Gastropod	*Anchura decemlirata*	infaunal	deposit/suspension feeder
Gastropod	*Anchura sp.*	infaunal	deposit/suspension feeder
Cephalopod	*Nautilus sp. nov. (=?Eutrephoceras)*	nektonic	carnivore
Cephalopod	*Placenticeras?*	nektonic	carnivore
Cephalopod	*Scaphites?*	nektonic	carnivore

Table 9: HITCHITEE CREEK MOLLUSCS

Class	Species	Substrate relationship	Trophic level
Bivalve	*Exogyra ponderosa*	epifaunal	suspension feeder
Bivalve	*Anomia argentaria*	epifaunal	suspension feeder
Cephalopod	*Placenticeras benningi*	nektonic	carnivore

Cusseta Formation Localities

HANNAHATCHEE CREEK

The Hannahatchee Creek assemblage was a moderately diverse community, with 16 molluscan species (Table 10). Bivalves account for 81% of the molluscan fauna; *Crassostrea cusseta, Idonearca carolinensis*, and *Cyprimeria depressa* are the dominant species. *C. cusseta* occurred here as a bioherm, and many were extensively bored by clionid sponges, a euryhaline element. Modern *Crassostrea* is very tolerant of reduced and/or fluctuating salinity, and beds form patches and elongate reefs in coastal bays and estuaries where salinity is below 34 ‰ (Scott, 1974). Infaunal bivalves account for only slightly more than half of the molluscan taxa (54%); 100% are suspension feeders. There is abundant fossil wood at this locality, much of it bored by clams. The fauna also included selachians, dinosaurs, turtles, and crocodylians. This assemblage occurs in clayey fine sand and silty clay. The faunal composition, lignite, sediment type, and carbon isotope values in the upper mesohaline to lower polyhaline range indicate a brackish estuary.

FLORENCE

The molluscan assemblage recovered from an exposure of the Cusseta Formation near Florence was a relatively diverse (19 species) community consisting entirely of bivalves (Table11). Suspension feeders accounted for 89%, and although infaunal species dominate at 58%, the community also contained several epifaunal species. These include *Anomia argentaria, Barbatia lintea*, and the oysters *Exogyra ponderosa erraticostata,*

Crassostrea cusseta, and *Flemingostrea pratti*. No other molluscan groups have been recovered from this locality, however, other fauna include *Hamulus onyx*, crocodylians, and selachians. The assemblage occurred in sediments described as gray to greenish-gray marine sands and clays, calcareous in different layers, with calcareous concretions. The sediment type and the presence of *Barbatia* suggests a protected lagoon of comparatively normal marine salinities.

Table 10: HANNAHATCHEE CREEK MOLLUSCS
(From Schwimmer, 1986)

Class	Species	Substrate relationship	Trophic level
Bivalve	*Idonearca carolinensis*	infaunal	suspension feeder
Bivalve	*Pachycardium stantoni*	infaunal	suspension feeder
Bivalve	*Pachycardium spillmani?*	infaunal	suspension feeder
Bivalve	*Granocardium alabamense*	infaunal	suspension feeder
Bivalve	*Protocardia vaughani*	infaunal	suspension feeder
Bivalve	*Trigonarca ?maconensis*	semi-infaunal	suspension feeder
Bivalve	*Exogyra ponderosa erraticostata*	epifaunal	suspension feeder
Bivalve	*Crassostrea cusseta*	epifaunal	suspension feeder
Bivalve	*Cyprimeria depressa*	infaunal	suspension feeder
Bivalve	*Aphrodina regia*	infaunal	suspension feeder
Bivalve	*Pecten? sp.*	epifaunal	suspension feeder
Bivalve	*Pecten? sp.*	epifaunal	suspension feeder
Bivalve	*Inoceramus sp.*	epifaunal	suspension feeder
Gastropod	*Turritella mortoni*	infaunal	suspension feeder
Cephalopod	*Eutrephoceras sp.*	nektonic	carnivore
Cephalopod	*Placenticeras placenta*	nektonic	carnivore

Table 11: FLORENCE MOLLUSCS
(From Veatch and Stephenson, 1911; Stephenson, 1914)

Class	Species	Substrate relationship	Trophic level
Bivalve	*Nucula percrassa*	infaunal	deposit feeder
Bivalve	*Leda (=Nuculana) longifrons*	infaunal	deposit feeder
Bivalve	*Trigonarca sp.*	semi-infaunal	suspension feeder
Bivalve	*Arca ?*	epifaunal	suspension feeder
Bivalve	*Barbatia (Polynema) lintea*	epifaunal	suspension feeder
Bivalve	*Barbatia sp.*	epifaunal	suspension feeder
Bivalve	*Flemingostrea pratti*	epifaunal	suspension feeder
Bivalve	*Ostrea sp. nov.(=?Crassostrea cusseta)*	epifaunal	suspension feeder
Bivalve	*Exogyra ponderosa erraticostata*	epifaunal	suspension feeder
Bivalve	*Trigonia (=?Scabrotrigonia) bartrami*	infaunal	suspension feeder
Bivalve	*Anomia argentaria*	epifaunal	suspension feeder
Bivalve	*Crassatellites (=Crassatella) roodensis*	infaunal	suspension feeder
Bivalve	*Cardium (=Pleuriocardia) eufaulense*	infaunal	suspension feeder
Bivalve	*Protocardia vaughani*	infaunal	suspension feeder
Bivalve	*Cyprimeria depressa*	infaunal	suspension feeder
Bivalve	*Aphrodina regia*	infaunal	suspension feeder
Bivalve	*Cyclothyris (=Cyclorisma) alta*	infaunal	suspension feeder
Bivalve	*Cymbophora lintea*	infaunal	suspension feeder
Bivalve	*Corbula carolinensis (=Caryocorbula oxynema)*	infaunal	suspension feeder

CONCLUSIONS

The results of this study show a very warm Late Cretaceous coastal paleoenvironment, characterized by significant freshwater input contributing to an extensive network of coastal bays, lagoons, estuaries, and swamp forests. Paleobotanical analysis indicates a terrestrial mean annual temperature of about 27°C during the Late Cretaceous, consistent with other studies of Late Cretaceous North American terrestrial climates. This is considerably warmer than modern terrestrial mean annual temperatures, which are about 19.3°C for the Gulf Coast of North America (National Oceanic and Atmospheric Administration).

Oxygen isotope data obtained from molluscan carbonate indicate mean sea surface paleotemperatures of 26.8°C for the Santonian, 23.5°C for the early Campanian, and 28.8°C for the late Campanian. These paleotemperatures are generally consistent with other studies of Late Cretaceous paleoclimate. Several studies (Schönfeld et al., 1991; Huber et al., 1995; Huber 1998; Fassell and Bralower, 1999; Norris et al., 2001; Skelton, 2003 *in* Skelton et al, 2003) of the Late Cretaceous paleoclimate demonstrate that maximum warmth occurred in the Turonian, with an estimated maximum sea surface temperature of 32°C. Following the mid-Cretaceous thermal maximum, gradual cooling began to take place, with fluctuations, until the late Campanian when another, albeit smaller, temperature excursion took place (Frakes, 1999). This same fluctuating paleoclimate pattern following the mid-Cretaceous thermal maximum can be seen in the results of this study, with relatively warm temperatures in the Santonian, followed by

slightly cooler temperatures in the early Campanian, then maximum warmth in the late Campanian.

Paleotemperatures from the molluscan carbonate data are quite warm relative to modern sea surface temperatures. Modern global mean SST is about 16.0°C, whereas North American Gulf Coast mean water temperature is approximately 21.8°C (National Oceanic and Atmospheric Administration). Conversely, paleotemperatures derived from phosphatic bone or tooth samples are somewhat cooler than expected, possibly reflecting the migratory lifestyle of the marine vertebrates from which the samples were obtained.

Regarding the usefulness of carbon isotopes for the determination of paleosalinity, the values obtained in this study are broadly compatible with the paleoecological results. However, there was considerable variation in some of the data, with some extremely anomalous values; the suggested salinity values from the chalk sample do not reflect the open-ocean, full marine environment from which the sample came. Although stable carbon isotopes are less subject to diagenesis than are oxygen isotopes, the precise relationship between $\delta^{13}C$ and salinity, temperature, and productivity is complex, therefore, carbon isotope methods are best used in conjunction with other methods, particularly detailed analysis of the paleocommunity.

Strontium isotope ratios are a potentially useful tool for the determination of paleosalinities, as well as for geologic age determination. A more extensive study of strontium isotope ratios, with samples obtained from known freshwater and fully marine deposits, and from deposits with well-constrained age assignments, would elucidate the utility of this method for paleoceanographic and stratigraphic analyses.

Paleoclimate reconstruction of the subtropical Late Cretaceous has been somewhat hampered by the lack of geochemical data. Much of the research has focused on the mid-Cretaceous thermal maximum, and/or on the end-Cretaceous extinction event. Research has also centered on the polar latitudes in the interest of answering the question of the existence of polar ice-caps in the Late Cretaceous. Deep-ocean sediments (the source of much paleoclimate data) of Late Cretaceous age are scarce. Yet, southeastern North America contains a rich store of paleodata to add to the global paleoclimate record, especially for a time and region for which data is sparse. This study has shown that regional fossil-bearing beds in Georgia and Alabama can provide useful and viable paleoclimate information of modern global climatic significance.

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